MODELING OF COASTAL OCEAN FLOW FIELDS

John S. Allen
College of Oceanic and Atmospheric Sciences
Oregon State University
104 Ocean Admin Building
Corvallis, OR 97331-5503
phone: (541) 737-2928   fax: (541) 737-2064 (Fax) email: jallen@oce.orst.edu

LONG-TERM GOALS

To understand the dynamics of physical oceanographic circulation processes on continental shelves and slopes with emphasis on the mechanisms involved in across-shelf transport.

SCIENTIFIC OBJECTIVES

To apply numerical circulation models to process studies and to simulations of observed continental shelf and slope flow fields to help achieve understanding of the flow dynamics.

APPROACH

Numerical finite-difference models based on the primitive equations, balance-type intermediate equations, and the shallow- water equations are applied to two- and three-dimensional flow problems relevant to the dynamics of continental shelf and slope flow fields. At present, both the Blumberg-Mellor sigma coordinate POM model and the SPEM model are being utilized for studies with the primitive equations. A shallow-water equation model has been developed and applied to studies involving vorticity dynamics of currents in the nearshore surf zone. The numerical experiments are supplemented with analytical studies whenever possible.

WORK COMPLETED

Model studies of two-dimensional, time-dependent, wind-forced, stratified downwelling circulation on the continental shelf (Allen and Newberger, 1996) have shown that the near-bottom offshore flow can develop time- and space-dependent fluctuations involving spatially-periodic separation and reattachment of the bottom boundary layer. This results in the formation of slantwise circulation cells with horizontal scales 2-4 km and vertical scales 20-60 m. Based on the observation that the potential vorticity, initially less than zero everywhere, is positive in the region of the fluctuations, this behavior was identified as finite amplitude slantwise convection resulting from a symmetric instability. To further support that identification, a direct stability analysis of the forced, time-dependent, downwelling circulation would be useful, but is difficult because the instabilities develop

as an integral part of the evolving flow field. Consequently, we have pursued a follow-up study to examine the linear stability of a near-bottom oceanic flow over sloping topography with conditions dynamically similar to those in the downwelling circulation and to establish a link between the instabilities observed in the wind-forced downwelling problem and the results of recent theoretical studies of bottom boundary layer behavior in stratified oceanic flows over sloping topography (e.g., Garrett, MacCready, and Rhines, 1993). These objectives have been addressed by investigating the two-dimensional linear stability and the nonlinear behavior of the steady, inviscid, "arrested Ekman layer" solution produced by transient downwelling in one-dimensional models of stratified flow adjustment over a sloping bottom. Further process studies addressing both two and three-dimensional aspects of symmetric instabilities in bottom boundary layers have been undertaken.

Numerical experiments addressing the nature of nonlinear, finite amplitude shear instabilities of alongshore currents in the surf zone through the solution to idealized, forced, dissipative, initial-value problems have been performed. Bottom topographies with both a constant slope (i.e., a plane beach) and with a shore-parallel sand bar are used with periodic boundary conditions in the alongshore direction. Forcing effects from obliquely incident breaking surface waves are approximated by an across-shore varying, steady force in the alongshore momentum equation. Idealized forcing and forcing determined from the formulation of Thornton and Guza (1986) are utilized. Dissipative effects are modeled by linear bottom friction.

Solutions to finite difference approximations in sigma coordinates to an iterated geostrophic intermediate model, along with semi-implicit and explicit versions of the primitive equations, have been obtained for studies assessing the balanced dynamics of rotating, stratified flows over O(1) bottom topographic variations. A new approximate extended-geostrophic model for balanced motion governed by the shallow water equations has been derived by using a small Rossby number expansion in Hamilton's Principle. Analytical solutions for coastal Kelvin waves are utilized to clarify the issue of appropriate boundary conditions for the balance equations.

RESULTS

A linear stability analysis of the steady, inviscid, "arrested Ekman layer" (Allen and Newberger, 1998) shows that this flow is unstable to symmetric instabilities and confirms that a necessary condition for instability is positive potential vorticity in the bottom layer. Numerical experiments show that the unstable, time-dependent, nonlinear behavior in the boundary layer involves the formation of slantwise circulation cells with characteristics similar to those found in the wind-forced downwelling circulation and the development of weak stable stratification close to that corresponding to marginally stable conditions with zero potential vorticity.

Numerical experiments (Allen, Newberger, and Barth, 1998) show that symmetric instabilities develop and form circulation cells in the bottom boundary layer in the basic

two-dimensional spin-down problem of a depth-independent coastal jet in a stratified ocean over sloping continental shelf topography when the transient Ekman transport in the bottom boundary layer is down slope (Figure 1). Preliminary results from three-dimensional spin-down and wind-forced downwelling experiments indicate that finite amplitude symmetric instabilities can develop in the bottom boundary layer. These typically form circulation cells similar to those found in two-dimensions. These cells subsequently develop secondary instabilities that result in time-dependent disturbances of larger horizontal scale.

In the study of nonlinear shear instabilities of alongshore currents in the surf zone over plane beaches (Allen, Newberger and Holman, 1996), the nature of the flow depends on a dimensionless parameter Q, which is the ratio of an advective to a frictional time scale. For Q smaller than a critical value QC, the forced alongshore current is unstable. The behavior of the instability depends on the value of DQ = QC - Q. For small positive DQ, propagating disturbances grow and equilibrate with constant amplitude at the wavelength L of the most unstable linear mode. For larger DQ, unstable waves of length L grow initially but subsequently break down into longer wavelength, nonlinear, propagating, steady or unsteady wavelike disturbances. In contrast, with sand bar topography and with forcing from the Thornton-Guza (1986) submodel (Slinn, Allen, and Holman, 1997), as the effective DQ is increased, the flow becomes increasingly unsteady exhibiting a transition from equilibrated shear waves to a turbulent shear flow. The results with sand bar topography point to the possible existence in the nearshore surf zone of an energetic eddy field associated with instabilities of the alongshore current.

In Allen and Holm (1996) it was shown that, by varying the expansion utilized in Hamilton's Principle a family of different approximate Hamiltonian models could be derived. For each member of the family the functional form of the potential vorticity, conserved on fluid particles, and of the kinetic energy contribution to the globally conserved energy can be prescribed. A particular new model with higher order dynamical consistency, and thus likely increased accuracy, is derived. In Allen, Gent, and Holm (1997), it is found that, compared with other proposed boundary conditions for the balance equations, the boundary conditions derived in Allen (1991) give the most accurate approximate solutions for Kelvin waves.

IMPACT/APPLICATIONS

Studies of the two-dimensional response of a stratified coastal ocean model with realistic stratification and continental shelf topography to downwelling favorable winds show new flow features. These include the formation and structure of downwelling fronts and the development of finite amplitude symmetric instabilities in a bottom layer with positive potential vorticity. The occurrence of symmetric instabilities in the bottom boundary layer appears to be a potentially important feature of transient downwelling circulation on the continental shelf. The results of the study of nonlinear shear instabilities of alongshore currents in the nearshore surf zone indicate the possible existence over plane beaches of

new finite-amplitude shear waves with properties not predicted by linear theory and the possible presence over barred beaches of an energetic eddy field.

TRANSITIONS

RELATED PROJECTS

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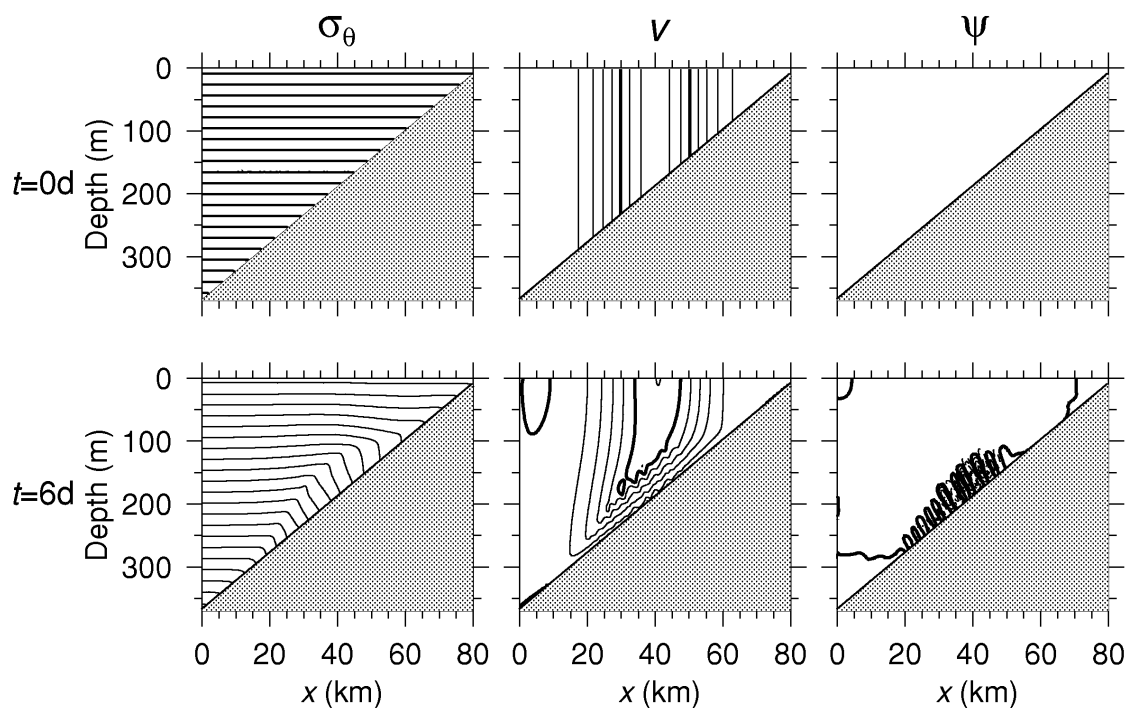
Figure 1. Results of a numerical experiment for a two-dimensional spin-down problem (Allen, Newberger and Barth, 1998). Fields of density σ_θ, alongshore velocity v, and streamfunction ψ. $N^2(t = 0) = 2.25 \times 10^{-4}$ s^{-2}, $\max v(t = 0) = 0.75$ m s^{-1}, horizontal diffusion coefficient $A_H = 4$ m^2 s^{-1}, bottom slope $\alpha = 0.0045$, slope Burger number $S = \alpha^2 N^2/f^2 = 0.42$, $\Delta x = 0.25$ km, and 60 σ levels. Contour intervals are 0.4 kg m^{-3}, 0.1 m s^{-1} and 0.1 m^2 s^{-1}.